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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

*Technical Memorandum 33-537*

*Furlable Spacecraft Antenna Development:  
An Interim Report*

*R. E. Oliver*

*A. H. Wilson*

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JET PROPULSION LABORATORY  
CALIFORNIA INSTITUTE OF TECHNOLOGY  
PASADENA, CALIFORNIA

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## PREFACE

The work described in this report was performed by the Engineering Mechanics Division of the Jet Propulsion Laboratory.

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## ABSTRACT

Activities at JPL directed toward the development of large furlable spacecraft antennas using conical main reflectors are described. Two basic antenna configurations which utilize conical main reflectors have been conceived at JPL and are under development. In the conical-Gregorian configuration each ray experiences two reflections in traveling from the feed center to the aperture plane. In the Quadreflex (four reflection) configuration, each ray experiences four reflections, one at each of two sub-reflector surfaces and two at the main conical reflector surface.

The RF gain measurements obtained from 1.83-m (6-ft) and 0.762-m (30-in.) models of the conical-Gregorian and Quadreflex concepts respectively were sufficiently encouraging to warrant further development of the concepts.

## I. INTRODUCTION

Several potential spacecraft missions, particularly those involving flights to the outer planets, will require the use of communication systems capable of transmitting data at higher rates than can be provided by current-state-of-the-art systems. It has been concluded by those familiar with all aspects of spacecraft communication systems that the most promising approaches toward increasing data rate are to: (1) increase the size of the spacecraft antenna, and (2) increase the operating radio frequency.

Owing to limitations on shroud dimensions, increasing spacecraft antenna reflector diameters beyond, say, 4 meters dictates the use of furlable antenna reflectors which can be unfurled in flight after jettisoning the shroud. Increasing the operating radio frequency of the antenna places severe surface accuracy requirements on the reflector elements of the antenna system. The operating radio frequency (RF) is in the cm range, increasing from the S-band operation for the Mariner spacecraft to X- and K<sub>u</sub>-bands. The combination of requirements (large size, furlability, and extreme surface accuracy) calls for advances in antenna reflector technology beyond that used in past flight projects.

Spacecraft high-gain antennas have traditionally used a paraboloidal main reflector with either a focal point or Cassegrainian feed. Most of the current antenna development activities by both government and industrial organizations appear to be directed toward the development of antennas based on the paraboloid-Cassegrainian configuration (Refs. 1, 2). While significant advances have been made in the design of furlable paraboloidal antenna reflectors, there are inherent problems associated with this configuration. Concepts developed to date generally involve the approximation of the desired doubly curved paraboloidal main reflector surface by a number of flat or singly curved elements or by doubly curved mesh elements

usually involving adverse curvatures; that is, the elements tend to bulge in the wrong direction. This tendency has led to the use of a larger number of smaller elements and a consequent increase in the number and weight of support elements.

While the development of very large, furlable, lightweight and accurate paraboloidal antenna reflectors is still in progress throughout the industry, development efforts have also been directed toward new basic configurations involving singly curved, conical main reflectors (Refs. 3-7). The primary impetus for this approach is the elimination of some of the basic problems associated with the double curvature of a paraboloid.

The present report describes the recent activities at JPL which have been directed toward the development of technology required to produce large, furlable, conical main reflector antennas.

## II. BASIC CONCEPTS CONSIDERED

### A. Conical-Gregorian Antenna

The conical-Gregorian antenna was conceived at JPL by A. Ludwig (Ref. 3). The basic principles of this concept are illustrated in Fig. 1. The main reflector surface is a frustum of a cone of half angle  $\theta$  produced by rotating a straight line EF about the antenna axis. The subreflector surface is generated by rotation of a segment AB of a parabola about the antenna axis. The axis CD of the generator parabola passes through the effective center D of the feed horn, and the focus of the parabola coincides with the feed center D. A ray emanating from the feed center D and striking the subreflector at, say, G is reflected toward the main reflector. This ray is then reflected from the main reflector at, say, H, and the emerging ray from H through I is parallel to the antenna axis. It can be shown, also, that the path lengths of all rays from the feed center D and experiencing specular reflections at the subreflector surface and at the main conical reflector surface and extended to any plane normal to the antenna axis and to the right of the main reflector aperture plane through F are equal.

From a structural view point, some potential advantages of the conical-Gregorian antenna are obvious. The conical main reflector surface, being developable from a planar surface, eliminates the adverse curvature effect of the doubly curved surface, lends itself to simple fabrication techniques and is compatible with simple furling schemes. From an RF viewpoint, the advantages are less obvious. They include better utilization of the radiated energy from the feed, insensitivity to defocussing, elimination of surface reflectivity RF loss by the possibility of replacing the mesh of the parabolic concept by a continuous surface material, and the reduction of surface deviation RF loss by elimination of the adverse curvature effect.

A potential disadvantage of the conical-Gregorian antenna concept is the inherently large aperture area blockage due to the subreflector. The subreflector, having a diameter slightly less than one-half the outer diameter of the main reflector, produces a primary aperture area blockage of about 22% as compared to less than 10% for typical Cassegrainian feed paraboloidal antennas. This disadvantage is at least partially offset by the RF advantages mentioned above. Another disadvantage is associated with

the size of the subreflector, namely its weight, which may be several times the weight of the subreflector for a Cassegrain feed paraboloidal antenna of equal main reflector diameter.

Several 1.83-m (6-ft) diameter models of the conical-Gregorian antenna have been built and tested at JPL (Refs. 4-6). The first model which was tested for RF gain performance is shown in Fig. 2. It is a non-furlable model, although the design initially included a furling capability. The main conical reflector is made of 0.203-mm (0.008-in.) thick fiberglass which is metallized with copper to provide RF reflectivity. Eight panels are hinge-connected to eight radial arms which are, in turn, hinge-connected to the central hub. For furling, these radial arms were to be folded toward the antenna axis to produce a configuration similar to that shown in Fig. 3.

This model was initially only partially successful in that it would not produce a satisfactorily conical shape in the earth's gravitational field. In order to obtain some preliminary RF data concerning the basic feasibility of the concept, this model was rigidized by spray-coating the back side of the cone with polyurethane foam. This process, of course, destroyed the furling capability but did provide a relatively crude "boiler plate" model suitable for RF testing on the JPL antenna range.

The results of range measurements of the gain of this antenna (in the K<sub>u</sub>-band frequency range) were encouraging. Quantitative results of RF tests of the conical-Gregorian antenna model are reported separately in Ref. 4. (The present report is generally limited to the mechanical and structural aspects of antenna development.) In view of the encouraging results of RF tests of this relatively crude boiler plate model, effort was directed toward developing more sophisticated furlable models.

Figure 4 shows an eight-panel model in which the fiberglass was replaced by 0.203-mm (0.008-in.) thick stainless steel sheets. Figure 3 shows this model in the furled configuration. It was found that this model was unsuccessful in that it would not maintain a sufficiently conical surface under gravity loading, with its axis horizontal, as required for antenna range testing.

The next-generation model of the conical-Gregorian antenna is shown in Fig. 5 in its unfurled configuration and in Fig. 6 in its furled configuration.

The cone is formed by six panels of 0.508-mm (0.020-in.) aluminum skin supported by six radial arms. The subdish support was modified to a three-point support truss to accommodate the furled configuration as shown in Fig. 6.

Another significant design improvement is shown in Figs. 5 and 6. Folding stiffeners are attached to the cone panels near their outer and inner edges. In principle, these stiffeners are attached to the panels by line hinges and are spring-loaded so that in the unfurled configuration they are drawn up against stops such that the stiffener sheets are normal to the conical reflector surface. These stiffeners serve two purposes. In addition to limiting gravity distortion, they force the reflector panels to assume the proper circular shapes at their outer and inner edges. RF performance tests on this antenna indicate a gain of 41.80 dB at X-band, a gain of 47.20 dB at  $K_u$ -band, and an area-weighted RMS surface deviation of about 0.203 mm (0.008 in.).

Other versions of the conical-Gregorian antenna are shown in Figs. 7 through 10. These are referred to as furlable ring-membrane conical-Gregorian antennas and differ from the previous conical-Gregorian antenna by the manner in which the furlable cone is constructed. The conical reflector surface is formed by stretching 0.0254-mm (0.001-in.) thick aluminized Mylar membrane between two rings, one fixed and one furlable, which establish registration circles on the desired cone.

In the version shown in Fig. 7, the outer U-section ring is collapsible so that it can be bent (without yielding) into a serpentine shape as shown in Fig. 8. This ring is supported at six points about its circumference by radial arms hinge-connected to the central hub. Three of these arms fold up toward the antenna axis while the other three have knee hinges to accommodate the alternating up and down lobes of the serpentine configuration of the furled ring. This type of design proved that the membrane idea was valid, but the stiffness of the deployed outer ring was somewhat insufficient to provide an acceptable outer circle.

The design of Fig. 9 was devised to provide the required increased stiffness. The outer ring of this antenna is supported by two sets of spokes much like a bicycle wheel rim is supported from its hub. Figure 10 shows the antenna in its furled configuration. The outer ring itself is made of

flat, 1.02-mm (0.040-in.) thick by 3.81-cm (1.5-in.) wide 6061-T6 aluminum to which has been added a 2.54-cm (1-in.) by 2.54-cm (1-in.) plastic ell-section to provide greater out-of-plane bending stiffness. Later tests have shown that, with a proper choice of material properties and ring section dimensions, this additional stiffener is not required (see, for example, Fig. 11). The RF test results indicated a gain of 41.55 dB at X-band and a gain of 46.56 dB at  $K_u$ -band, corresponding to efficiencies of 54.5 and 46.2% respectively.

The objective in considering ring-membrane constructions for the conical reflecting surface is to decrease the weight from that associated with the relatively thick panels required in the version shown in Fig. 5. The use of spokes to support the outer ring is also aimed at weight reduction. This approach eliminates the radial arms of the configuration shown in Figs. 7 and 8 and also permits the use of a much lighter and simpler outer ring.

Development activities on the latter two versions of the conical-Gregorian antenna are discussed in more depth in the component development section of this report.

#### B. Quadreflex Antenna

The Quadreflex antenna, as the name implies, involves four reflections of each ray emitted from, or entering, the antenna. The principle of this concept, which was introduced in Ref. 8, is illustrated in Fig. 12. The main reflector surface forms a frustum of a cone of half angle  $\theta$ . A central subreflector surface is generated by rotation about the antenna axis (through F and D) of a segment AC of a parabola. The axis of this generator parabola (through A and G') forms an angle  $2\theta$  with the antenna axis, and the focus of the generator parabola in the section view shown in Fig. 12 is at G'. The image of this focus, as reflected in the main conical reflector surface, is at G. An outer subreflector surface is generated by rotation, about the antenna axis, of a segment DE of an ellipse. The foci of this generator ellipse are at G and F, with F coincident with the phase center of the feed horn.

The parameters governing the geometry of the three conicoidal reflecting surfaces are chosen such that a typical ray emanating from the

feed horn follows a path such as that shown through F-H-I-J-K-L in Fig. 12. It can be shown that, for proper choices of parameters, all such rays emerge from the antenna parallel to the antenna axis, and all total path lengths from the feed horn through the four reflections and to a plane to the right of point B, and normal to the antenna axis, are equal.

This antenna concept has several potential advantages. All of the advantages associated with a singly curved conical main reflector are associated with this concept. Further, the subreflector diameters (e.g.,  $D_S$  in Fig. 12) can be made a small fraction of the outer diameter  $D_A$  of the main reflector. The direct blockage due to the subreflectors can be less than that associated with conventional paraboloidal Cassegrainian feed antennas.

A potential disadvantage of this concept is that four reflections from imperfect reflecting surfaces tend to degrade antenna performance. (This is opposed to two reflections in the conical-Gregorian and Cassegrainian-feed paraboloidal antenna concepts.) Thus, for equivalent random deviations from ideal surface shapes for each component, one would expect about a 40% higher effective overall rms surface deviation. To counter this disadvantage it can be argued, of course, that smaller tolerances can be maintained on the relatively small-diameter subreflectors, and therefore something less than a 40% increase in effective overall rms surface deviation can be achieved.

A 0.762-m (30-in.) diameter boiler-plate model of the Quadreflex antenna has been made and RF-tested (at  $K_u$ -band). This model is shown in Figs. 13 and 14. The main reflector forms a frustum of a 45-deg half-angle cone. An axial view of this model is shown in Fig. 15. Note that the direct aperture blockage due to the subreflectors is about 9% for this model.

Results of initial RF tests at  $K_u$ -band of this concept (60% efficiency) were considered sufficiently encouraging to warrant further development effort. Current effort is directed toward the design and fabrication of a 1.83-m (6-ft) diameter furlable model with a half-cone angle of 39 deg.

### III. COMPONENT DEVELOPMENT

While test results from relatively small models of both the conical-Gregorian and the Quadreflex antenna concepts indicate that these concepts can be competitive with conventional Cassegrainian feed paraboloidal antennas from the standpoint of overall antenna efficiency, additional development work is required to determine their applicability to actual spacecraft missions. Ultimately this will require fabrication and appropriate testing of full-size flight-type antennas. In view of the potentially high costs associated with full-scale antenna fabrication, it is important that the adequacy of all new structural component concepts be demonstrated either by test or appropriate analysis before commitment to a full-size design. The following sections describe such component development activities.

#### A. Solid Sheet Conical Reflector

As indicated in Section I-A, several 1.83-m (6-ft) diameter models of the conical-Gregorian antenna have been fabricated. The most successful model to date, from the standpoint of RF performance, is shown in Fig. 5. The main reflector conical surface is formed by 0.508-mm (0.020-in.) thick aluminum sheets. Hinged stiffeners near the outer and inner edges of the sheet panels tend to force the panels into the proper shape when the antenna is unfurled.

In order for this concept to be used in future spacecraft missions, models of larger size must be made and RF-tested. Present development effort is being directed toward the design, fabrication, and RF testing of a 4.57-m (14-ft) diameter version.

At first glance, it may appear that straightforward scaling laws can be applied to dimensions of the 1.83-m (6-ft) diameter model to produce a larger antenna design. It can readily be shown, however, that this is not the case. It is clear, for instance, that for equal overall antenna efficiencies, the rms deviations of reflecting surfaces from the proper surfaces must be scaled by a factor of unity. If, on the other hand, out-of-plane static bending deflections of the sheet panels due to earth gravity (during

ground RF testing) contribute significantly to these rms deviations, then the sheet thickness should be scaled approximately by the square of the scale factor for linear dimensions. This would result in a sheet thickness of 2.8 mm (0.11 in.) for a 4.57-m (14-ft) diameter antenna. Such a sheet thickness is, of course, impractical both from the weight standpoint and from the standpoint of furlability. Even when one considers materials other than aluminum, there is a basic conflict between the requirements for stiffness to limit static deflections and flexibility to permit small radius of curvature bending for furling.

The folding stiffeners used on the 1.83-m (6-ft) diameter model shown in Figs. 5 and 6 tend to resolve this conflict by providing a stiff panel structure in the unfurled configuration and a much more flexible panel structure when the stiffeners are folded away from their normal positions. Current development efforts are directed toward producing a panel-stiffener combination which will provide the required stiffeners to limit surface distortions due to gravity, be compatible with the furled configuration shown in Fig. 6, and still result in a reasonable antenna weight.

In order to evaluate panel and stiffener combinations for a 4.57-m (14-ft) diameter conical reflector for a conical-Gregorian antenna without making an entire reflector, the single panel test fixture shown in Fig. 16 was made. This fixture provides a means for positioning two adjacent radial arms of a six-panel reflector in either the furled or unfurled position. Also shown in Fig. 16 is a 0.508-mm (0.020-in.) thick (2024 aluminum) panel mounted on the radial arms. Two folding stiffeners are attached at quarter chord distances from the inner and outer edges, as can be seen in Fig. 17. The spring and stop arrangement for forcing the stiffeners into the proper position (normal to the reflector sheet) in the unfurled configuration is also visible in Fig. 17. The location of stiffeners at quarter chord points was based on a theoretical analysis of static deflections due to gravity.

Although the theoretical analysis indicates the quarter chord points as nearly optimum for two stiffeners, preliminary evaluation of the test panel indicates that the outer stiffener should be nearer the outer edge for this particular panel. The fixture will be used to evaluate other panels using different materials, sheet thicknesses, and stiffener arrangements. After

demonstrating that a suitable panel can be made, the present plan is to then fabricate a complete 4.57-m (14-ft) diameter conical reflector.

B. Furlable Ring-Supported Conical Reflector

Although the above-described sheet metal conical reflector concept has been demonstrated successfully in a 1.83-m (6-ft) diameter antenna model, there remains some doubt concerning the feasibility of that concept for larger antennas, particularly with respect to weight. In view of this uncertainty, another concept has been pursued in parallel. In this concept, the conical reflector is formed by a very lightweight reflecting material (e.g., metallized plastic film) stretched between two relatively rigid circular rings.

Two basic versions of this concept have been pursued. The following sections describe the results of development activities on this concept.

1. Rib-supported outer ring. The principle of the rib-supported outer ring version of the ring-supported conical reflector concept is shown in Fig. 7 (unfurled) and Fig. 8 (furled). The ring is made by two annular segments connected by a cylindrical web. In the unfurled configuration, the outer ring assumes a U-shaped section which provides relatively high stiffness resistance in both in-plane and out-of-plane bending of the ring. The three elements of the U-shaped section, however, are hinge-connected to permit local collapse of the section into a flat configuration. Locally collapsing the ring section in six areas around the circumference of the ring then allows the ring to be bent into a serpentine shape, as shown in Fig. 18, which also shows the arrangement of six arms used to support and properly position the outer ring in both the furled and unfurled configurations. The wire stitching method for providing the desired hinge action between ring elements is illustrated in Fig. 19.

Several potential problems are associated with this concept. The location and orientation of the ring are determined by the six outer ends of the support arms. Any inaccuracies or nonrepeatability of the positions of these outer ends will be reflected in deviations of the reflecting surface from the proper conical surface. Additional deviations from the proper surface will result from nonrepeatability (during the furling-unfurling cycle) of the ring section between support points. Thus considerable care must be

exercised in the design and fabrication of the several elements to eliminate backlash and local yielding (e.g., of the wires used in the hinges), which may result in serious nonrepeatability.

Another potential problem is associated with the loading of the outer ring due to radial tension in the reflecting surface material. This distributed tension produces out-of-plane bending and torsional loading of the ring section between supports. Resulting deflections of the ring between supports produce additional deviations of the reflecting surface from the proper conical surface. The ring must, therefore, be designed with adequate stiffness (i.e., appropriate material and section properties) to keep deflections due to reflecting surface tension within acceptable bounds.

There are several possible approaches toward establishing an acceptable ring design for a particular antenna application. One could, for instance, take an essentially trial-and-error approach in which guesses of appropriate material and section properties are made and then a ring is made and tried (measured or tested). Based on the results of this first trial, new guesses are made, and the process is repeated until a suitable ring is obtained.

Another approach is to establish an appropriate mathematical model of the ring structure, then analytically determine its deflection characteristics when subjected to the predicted loading. In many structural design situations, some combination of these approaches (empirical and analytical) is used. In the case of the collapsible ring section considered here, the application of either approach, or a combination of the two, is not straightforward. The complexity of the structural aspects of the wire-laced hinge joint makes it difficult, to say the least, to arrive at an appropriate second guess for material and section properties. This complexity also casts serious doubts on the adequacy of any reasonably simple mathematical model of the ring.

The U-section ring shown in Fig. 18 is actually the result of several iterations of the above-mentioned trial-and-error process. The primary objective of the efforts leading to this ring configuration was to confirm the basic feasibility of the concept. A secondary objective was to obtain some qualitative information concerning the characteristics and behavior of the

ring in the furled and unfurled configurations. It was intended that this information would be useful as a guide in arriving at a better design.

Partial success was achieved in meeting the two objectives. It was demonstrated that the ring shown in Fig. 18 is relatively rigid in the unfurled configuration and that it can be locally collapsed and folded into the desired serpentine configuration. Qualitative evaluation of the structural characteristics of the ring, however, revealed two serious deficiencies in this particular design. First, significant hysteresis was observed. It was observed that the out-of-plane displacement of a point on the ring due to an applied force did not always return to zero upon removal of the applied force. Second, it was observed that the stiffness (in bending and torsion) was not adequate to maintain the proper flat circular shape when the reflecting surface was attached.

The latter observation was anticipated (a thin-walled open section typically has a low torsional stiffness), and the development of a closed rectangular section ring was initiated by adding an additional cylindrical web to the ring. Rather than a complete ring, however, a 60-deg segment (one sixth of a complete ring) was made, as shown in Fig. 20. Bulkheads were placed in each end of this segment to maintain rectangular sections there. Note that for the serpentine furled configuration (Fig. 8) with six lobes (three up and three down), there are six points about the circumference of the ring at which the ring section is not required to collapse and at which, in fact, rigid bulkheads can be placed.

The purpose of making this test segment was to demonstrate the compatibility of the closed rectangular section ring with the serpentine furling configuration and to obtain quantitative data concerning the stiffness characteristics of this type of collapsible ring.

That the closed box section is compatible with the serpentine furling configuration was demonstrated by collapsing the segment and bending it as shown in Fig. 21. The extension on the right-hand side of the segment in Fig. 21 is a latch which locks the section in its rectangular shape in the unfurled configuration. These latches must be manually released in order to furl the ring, but automatically latch to produce the desired rectangular section when the ring is unfurled.

The one-sixth ring segment shown in Fig. 20 was also used in a test program to provide quantitative data concerning its stiffness characteristics. In this test program the ring segment was mounted in a test fixture which provided essentially built-in support conditions (restraint of all six degrees of freedom and maintenance of the rectangular section) at each end. The fixture also provided a means for applying known point loads near the center of the segment and normal to the plane of the ring. Measurements were made of the deflection of the ring segment at the point of load application as a function of applied load. Test data are presented in Figs. 22 and 23. Figure 22 shows load vs deflection for the as-built ring segment while Fig. 23 shows load vs deflection after ten folding cycles (to simulate furling and unfurling of a complete ring).

The test data for the as-built segment (Fig. 22) indicate a stiffness of about 478 N/m (273 lb/in.). After 10 folding cycles (Fig. 23) the stiffness decreased to about 464 N/m (265 lb/in.), showing only a 3% decrease in stiffness. This decrease in stiffness may be attributed to local yielding of the wire lacing and yielding of the sheets at the wire/sheet interfaces during the folding cycles. Nonlinearity and hysteresis apparent in the data may be attributed to nonperfect contact between the plates forming the ring segment (local backlash) and sliding contact at the plate interfaces during differential shearing deflection under loading.

In order to obtain a quantitative evaluation of the structural efficiency of the wire-laced hinge construction, a theoretical analysis was made of a ring with section dimensions identical to those of the test ring segment but without hinge joints (i. e., with continuous welded joints) between the plate elements. Analysis for a complete ring with six equally spaced simple (pin) supports indicates a stiffness, corresponding to the above-quoted experimentally determined stiffness, of 4720 N/m (2700 lb/in.).

Although an attempt was made in the test fixture to provide built-in supports, the actual support conditions were probably somewhat less rigid than built-in but more rigid than for pin supports. Thus the actual ring segment exhibits a structural efficiency of less than 10% when compared to an ideal, continuously welded ring. This relatively low efficiency can be attributed partially to the expected and required flexibility of the laced hinges in their normal hinge modes. It was suspected also that a significant

loss in efficiency was due to relatively low stiffnesses of the laced hinges in resisting shear deflections (both parallel and transverse to the hinge axes) and is possibly due to relatively low stiffnesses resisting relative motion between plates in directions normal to the hinge axes.

In an attempt to obtain quantitative evaluations of the relative importance of the several hinge stiffnesses, a digital computer structural analysis (using the ELAS program) was performed. In this analysis the ring segment was modeled by a number of rectangular plate elements with the wire-laced hinges simulated by line elements (beams) connecting adjacent plate elements at discrete points along the hinge lines. By varying the axial, shear, and bending stiffnesses of these line elements in the mathematical model, the relative importance of the several hinge stiffnesses (in shear, translation, and rotation) can be determined.

In order to investigate the effects of distortions of the ring section from its original rectangular shape, additional transverse bulkheads (in addition to those at the ends) were put into the mathematical model. In the first series of computer runs with the additional bulkheads, the bulkheads served only to maintain rectangular sections at intermediate stations along the ring segment. It was found that one and three such additional bulkheads produced negligible effects on the ring stiffness. In a second series of computer runs, the additional bulkheads not only maintained rectangular sections but also restrained relative shear deflections between adjacent plate elements at the bulkhead locations. The ring out-of-plane bending stiffness was found to be very sensitive to this type of additional bulkhead.

It was concluded from these results that, in order to provide an efficient structural ring, shearing motion between the webs and flanges must be restrained. These results suggest that the wire-stitched hinges must be replaced, at least at a few discrete places, with more effective hinges which prevent all relative motion between webs and flanges except the simple hinge rotation required for furling the ring. No further work on this hinged ring concept is anticipated because a new, more promising, ring concept was devised as described below.

2. Spoke-supported outer ring. An alternative approach to implementing the ring/membrane concept involves the old principle of supporting a ring by means of two families of spokes in the same manner that a bicycle

wheel rim is supported. All of the conical main reflector antenna concepts considered in this program require subreflectors located forward of the plane of the outer perimeter of the conical reflector. This subreflector itself, or a ring mounted to the subreflector support truss, provides a convenient hub to which one set of spokes can be attached. The base hub of the antenna provides a convenient location for attaching the other set of spokes.

While the spoke-supported ring principle is well-known and has, of course, been used extensively for decades, there was some skepticism expressed concerning its applicability to the conical antenna concepts mainly because of furlability requirements. Some of the skepticism may have resulted from unhappy experiences by individuals who had tried to straighten bent bicycle wheels.

In order to get a feeling for the problems associated with applying the spoke principle to a conical antenna, a simple test setup, using some of the existing hardware from the rib-supported ring conical-Gregorian antenna was assembled. This test setup is shown in Fig. 24. The previously built collapsible ring was supported by two sets of spokes (20 spokes in each set), and the six support arms were removed. It was demonstrated that the ring could be accurately located at each of the 20 spoke-attachment points. Results from this relatively crude demonstration were sufficiently encouraging to warrant pursuit of the concept at least to the extent of fabricating a 1.83-m (6-ft) diameter model for RF testing.

Figures 9 and 10 show the first version of a 1.83-m (6-ft) diameter spoke-supported ring-membrane conical-Gregorian antenna which was assembled and RF-tested. The outer ring in this model is a flat annulus with a section 1.02 mm (0.040 in.) thick and 3.81 cm (1.5 in.) wide and made of 6061-T6 aluminum alloy. A plastic ell section was added to the aluminum annulus to increase its out-of-plane bending stiffness. Subsequent experience indicates that this folding ell section can be eliminated through proper choices of ring section dimensions and material properties.

The outer ring of the antenna shown in Fig. 9 is supported at 40 points by two sets of spokes (40 spokes in each set). The forward set of spokes (i. e., on the illuminated side of the conical reflector) is made

of fiberglass tapes to minimize RF interference. The rear spokes (i. e., those on the nonilluminated side of the conical reflector) are steel wires. Furlability of the spoke-supported ring-membrane concept is demonstrated in Fig. 10.

The RF range tests of the spoke-supported ring/membrane antenna shown in Fig. 9 were encouraging. Measured gains were 41.55 dB for X-band and 46.56 dB for K-band, corresponding to an rms surface distortion of 0.762 mm (0.030 in.) (cf. 0.432-mm, 0.017 in. rms surface distortion for the sheet metal reflector shown in Fig. 5).

3. Membrane cone. The conical reflecting surface is formed by six 0.0254-mm (0.001-in.) thick aluminized Mylar gores. These gores are supported by radially oriented fiberglass tapes bonded on their non-illuminated sides as shown in Fig. 25. Each end of each tape is attached to a coil spring. The springs are then attached to the outer ring and to the inner hub as shown in Fig. 26. It was determined empirically that these springs tend to prevent even more serious puckering of the membrane than is evident in Fig. 26.

Current efforts are directed toward developing better techniques for attaching reflective surfaces to the inner and outer rings. Other development activity is being directed toward producing a spoke-supported ring/membrane configuration which is completely self-erecting. While the above-described models exhibit a strong initial tendency to assume the proper deployed configuration, there is a significant over-center action and there are statically stable partially erected positions of the ring.

4. Compensation for imperfect conical reflector surfaces. In concept, a perfectly conical surface can be formed by stretching a thin membrane or mesh material between two rigid circular rings which lie on the desired conical surface if there is no circumferential tension in the material. In practice, however, some finite circumferential tension is required to eliminate wrinkling or puckering of the material. This circumferential tension then causes the reflective surface material to deviate from the desired conical surface between the rigid rings. This effect has been referred to as the "lampshade" effect.

If the methods used for fixing the two rigid rings and for attaching the reflective surface material are such that axial symmetry is maintained in the ring loading and in the film or mesh tensions, then the resulting reflecting surface, although not conical, will be axially symmetric. Preliminary work has shown that it is possible to alter the shape of a subreflector to compensate for this deviation of the main reflector from its ideal conical shape. Such a compensation technique must preserve both the focusing characteristics of the reflector system as well as its equal path length characteristics.

It can be shown that, with reasonable restrictions on the continuity of the distorted shape, such a compensation is theoretically possible. The possibility of applying this compensation technique to the conical-Gregorian and Quadreflex antennas was considered. It is concluded that, although in principle compensation can be achieved for both antennas, it is practically more applicable to the Quadreflex antenna. This is due to the fact that the adverse lampshade effect causes a divergence of the received rays after reflection from the main reflector. The primary effect of the compensation technique is to increase the diameter of the parabolic subreflector for the conical-Gregorian antenna, whereas for the Quadreflex antenna, the primary effect of the compensation technique is an increase in the length of the parabolic subreflector (Fig. 12). Increasing the diameter of the subreflector of the conical-Gregorian antenna contributes directly to the already large primary aperture blockage.

In order to evaluate the feasibility of the compensation technique for the Quadreflex antenna, a digital computer program is being developed to determine the proper shape of the "parabolic" intermediate subreflector to compensate for a known nonconical main reflector. If it is determined that the technique is feasible, then this computer program may be used as a design tool.

5. Application of advanced composites. The possibility of using composites in the construction of spacecraft antennas is, of course, not a new concept. Various honeycomb constructions have been used in main paraboloidal reflectors and subreflectors for several years. The use of advanced composites for antennas is currently being introduced throughout

industry. Several companies have recently developed techniques for fabricating reflectors and other antenna components using advanced graphite/epoxy composites.

There are no current activities at JPL in the spacecraft antenna structures program directed toward developing new composite materials or fabrication techniques. The intent is rather to follow industry developments in advanced composite technology and to evaluate the potential advantages of using composite materials for particular antenna components. Evaluations of potential applications take into account antenna weight, performance, and cost.

Probably the most attractive feature available in advanced composite materials is a very low coefficient of thermal expansion. This feature holds the promise of eliminating problems associated with nonuniform temperatures within antenna structures. In addition, the availability of advanced composites which exhibit good structural characteristics (high strength, elastic modulus, and low density) makes them prime candidate materials for antenna construction.

#### IV. SUMMARY

During the past two and a half years, JPL has pursued the development of two microwave antenna concepts involving conical main reflectors. Results of development efforts to date have demonstrated the basic feasibility of both concepts, although further technology development is required to produce large-diameter flight-type antennas based on these concepts.

The development of the conical-Gregorian antenna is currently more advanced than that of the Quadreflex antenna. Several 1.83-m (6-ft) diameter furlable models have been fabricated and RF-tested. Results indicate overall efficiencies competitive with those achievable with furlable, paraboloidal, Cassegrainian-feed antennas. It remains to be demonstrated that larger, e.g., 4.57-m (14-ft) diameter, conical-Gregorian antennas can be designed and fabricated such that they offer significant advantages over more conventional paraboloidal antennas in the areas of performance, weight, reliability, or cost. Current activities are directed toward the design of such a larger conical-Gregorian antenna.

The basic feasibility of the Quadreflex antenna concept has been demonstrated only through RF testing of a small, 0.762-m (30-in.) diameter rigid model. Although this concept provides a potentially much more favorable furled-to-unfurled volume (and diameter) ratio than the conical-Gregorian concept, it has not been demonstrated that a lightweight furlable antenna based on this concept and exhibiting suitable performance characteristics can be fabricated. The next step toward such a demonstration will be the design, fabrication, and RF testing of a furlable 1.83-m (6-ft) diameter model.

Considerable progress has been made in the development of a furlable spoke-supported ring concept. This concept offers promise as a means of producing very lightweight furlable conical main reflectors for either conical-Gregorian antennas or for Quadreflex antennas.

## REFERENCES

1. Hamilton, E. C., et al., Large Erectable Antenna for Space Applications, General Dynamics Final Report, NASA CR-102522, September 30, 1969.
2. ATS F and G Large Aperture Antenna, GER 14038, Goodyear Aerospace Corporation, Akron, Ohio, April 1969.
3. Ludwig, A. C., "Large Spacecraft Antennas (Non-Paraboloidal Reflector)," in The Deep Space Network, Space Programs Summary 37-59, Vol. III, Jet Propulsion Laboratory, Pasadena, Calif., October 1969.
4. Ludwig, A. C., and Hardy, J., "Spacecraft Antenna Research: Preliminary RF Test of Conical Gregorian Antenna," in The Deep Space Network, Space Programs Summary 37-63, Vol. III, Jet Propulsion Laboratory, Pasadena, Calif., June 1970.
5. Fisher, J. G., "Development of a Conical-Gregorian High Gain Antenna," in The Deep Space Network, Space Programs Summary 37-63, Vol. III, Jet Propulsion Laboratory, Pasadena, Calif., June 1970.
6. Fisher, J. G., "Development of a Conical-Gregorian High Gain Antenna," in The Deep Space Network, Space Programs Summary 37-63, Vol. III, Jet Propulsion Laboratory, Pasadena, Calif., December 1970.
7. Bright, T., Evey, R., Sheppard, R., and Manson, R., "Systems Impact of a Conical Antenna for Planetary Communications," Preprint AAS-71-151, American Astronautical Society 17th Annual Meeting, Seattle, Washington, June 28-30, 1971.
8. Oliver, R. E., "Large Spacecraft Antennas: New Geometric Configuration Design Concepts," Jet Propulsion Laboratory, Pasadena, Calif., Quarterly Technical Review, Vol. I, No. 1, April 1971.

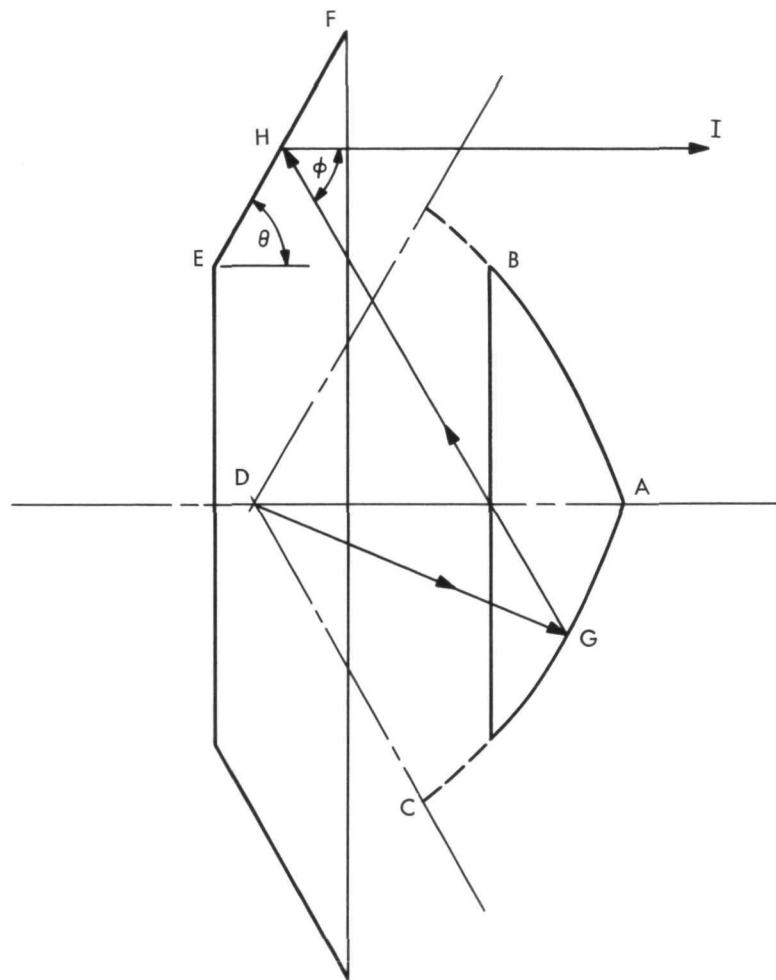


Fig. 1. Conical-Gregorian antenna



Fig. 2. The 1.83-m (6-ft) diameter rigid conical-Gregorian antenna



Fig. 3. The 1.83-m (6-ft) diameter furlable conical-Gregorian antenna with stainless steel panels (furled)

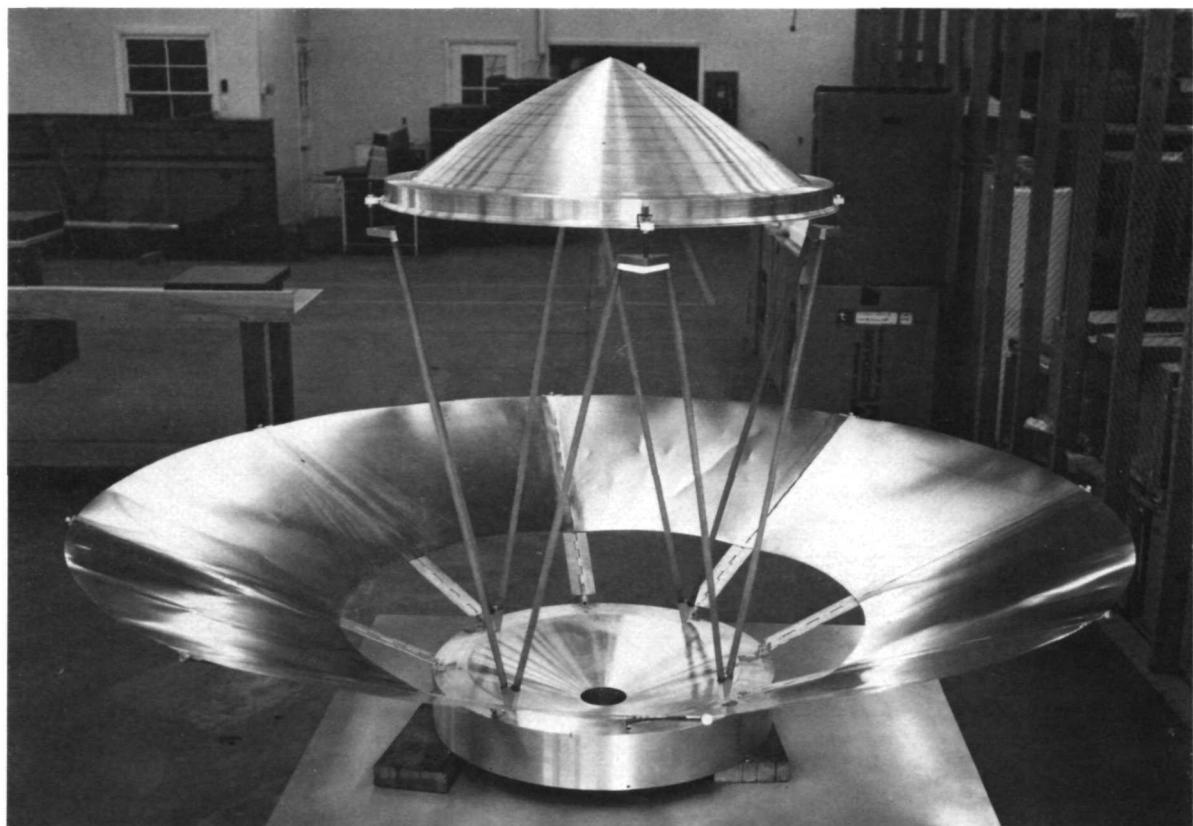


Fig. 4. The 1.83-m (6-ft) diameter furlable conical-Gregorian antenna with stainless steel panels (unfurled)

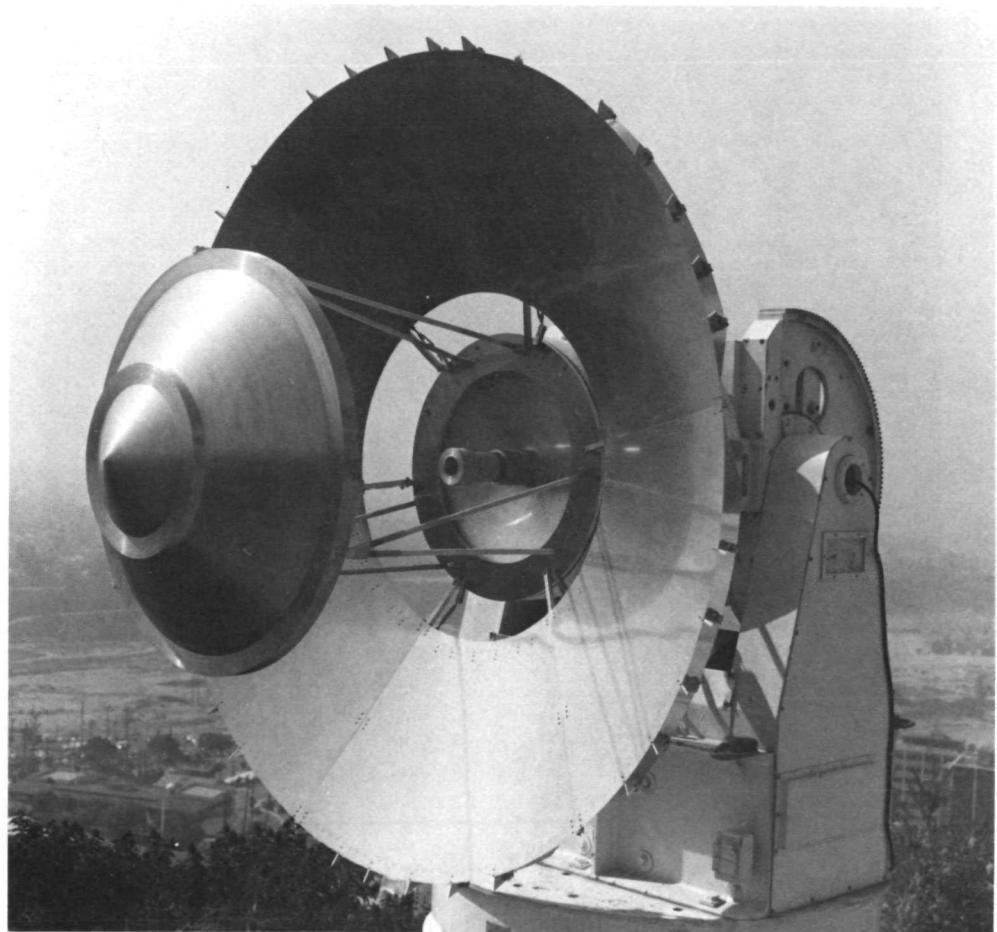


Fig. 5. The 1.83-m (6-ft) diameter furlable conical-Gregorian antenna with aluminum panels (unfurled)

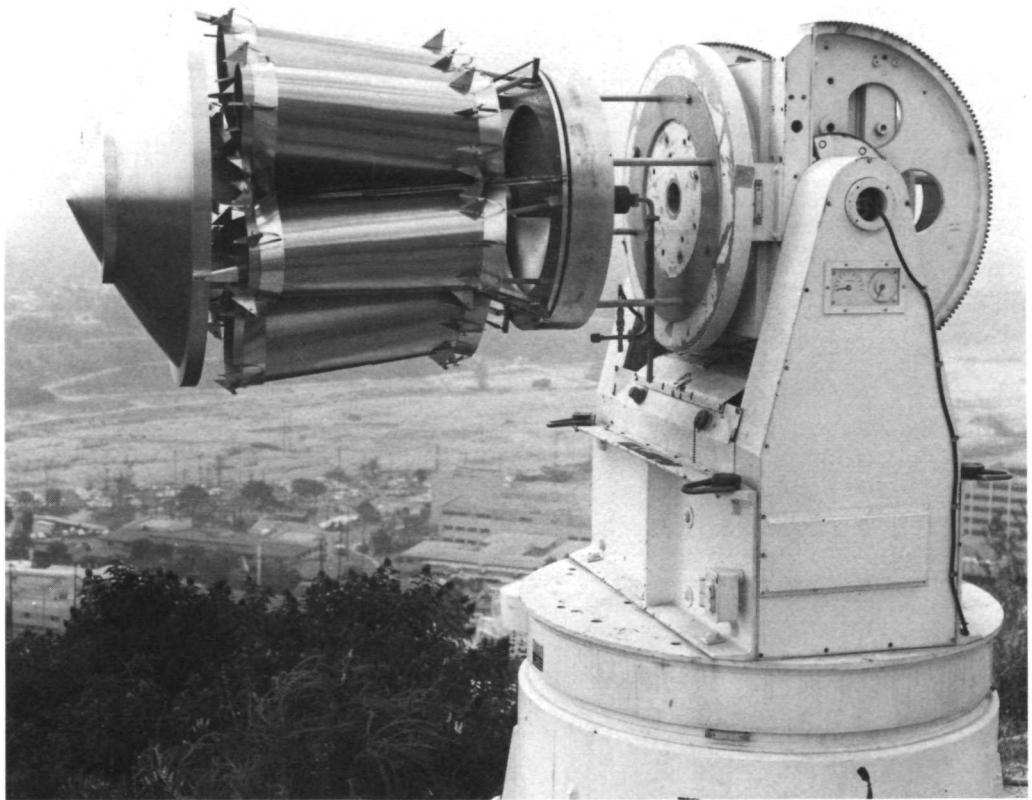


Fig. 6. The 1.83-m (6-ft) diameter furlable conical-Gregorian antenna with aluminum panels (unfurled)

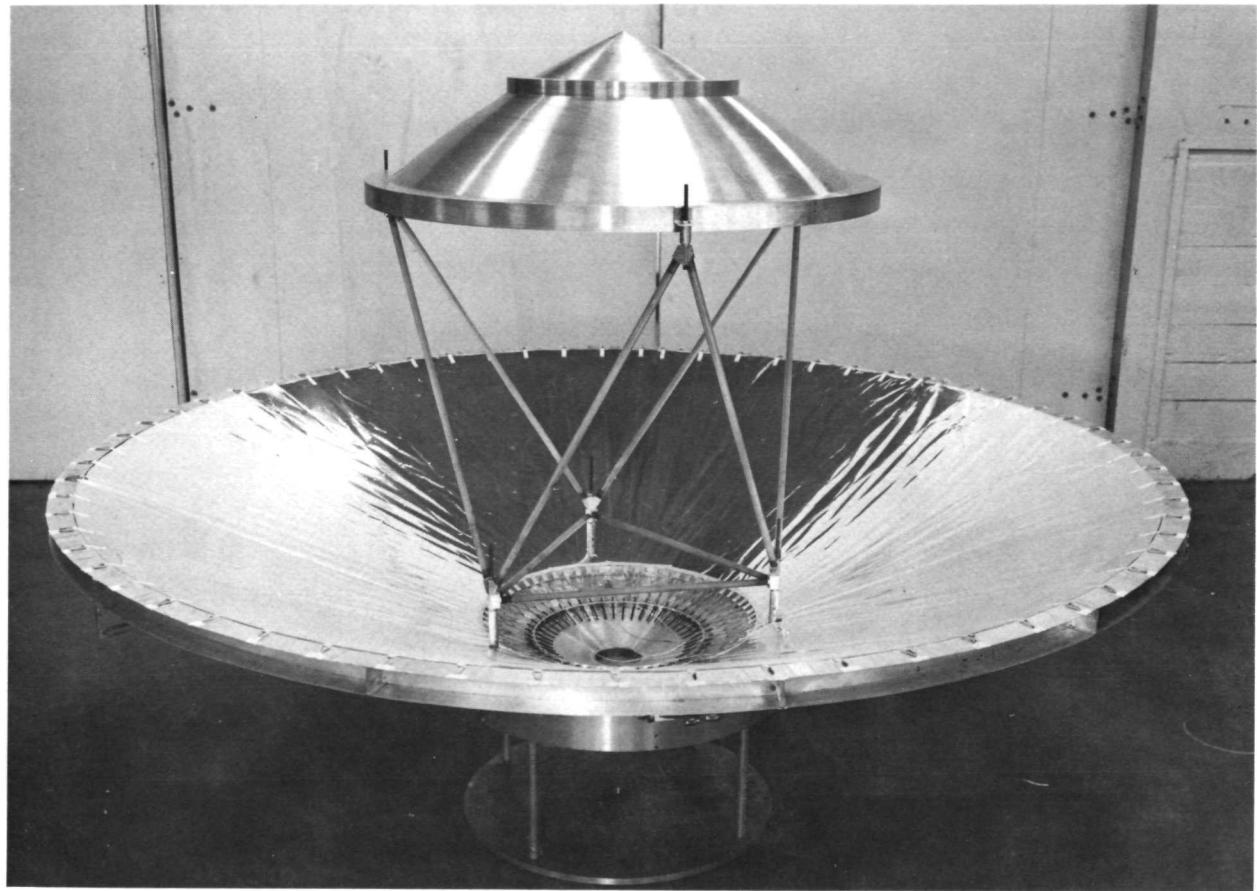


Fig. 7. The 1.83-m (6-ft) diameter furlable conical-Gregorian antenna-rib-supported ring-membrane design (unfurled)



Fig. 8. The 1.83-m (6-ft) diameter furlable conical-Gregorian antenna-rib-supported ring-membrane design (furled)

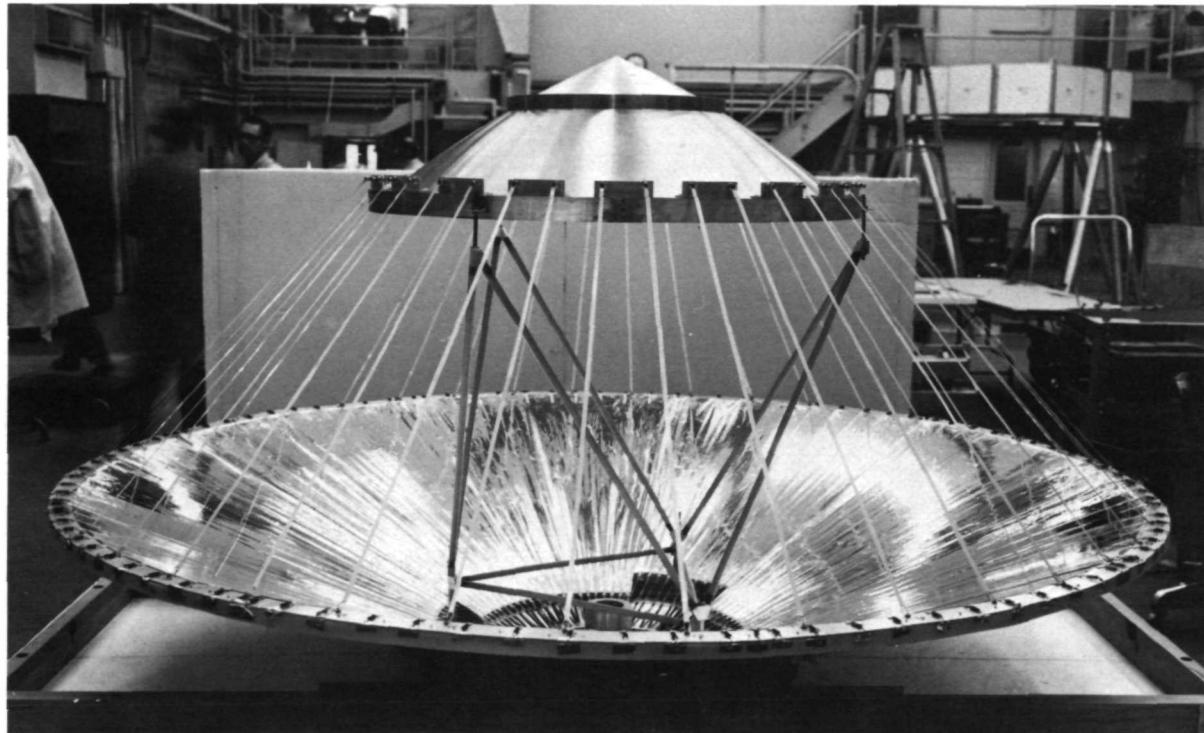


Fig. 9. The 1.83-m (6-ft) diameter furlable conical-Gregorian antenna-spoke-supported ring-membrane design (unfurled)

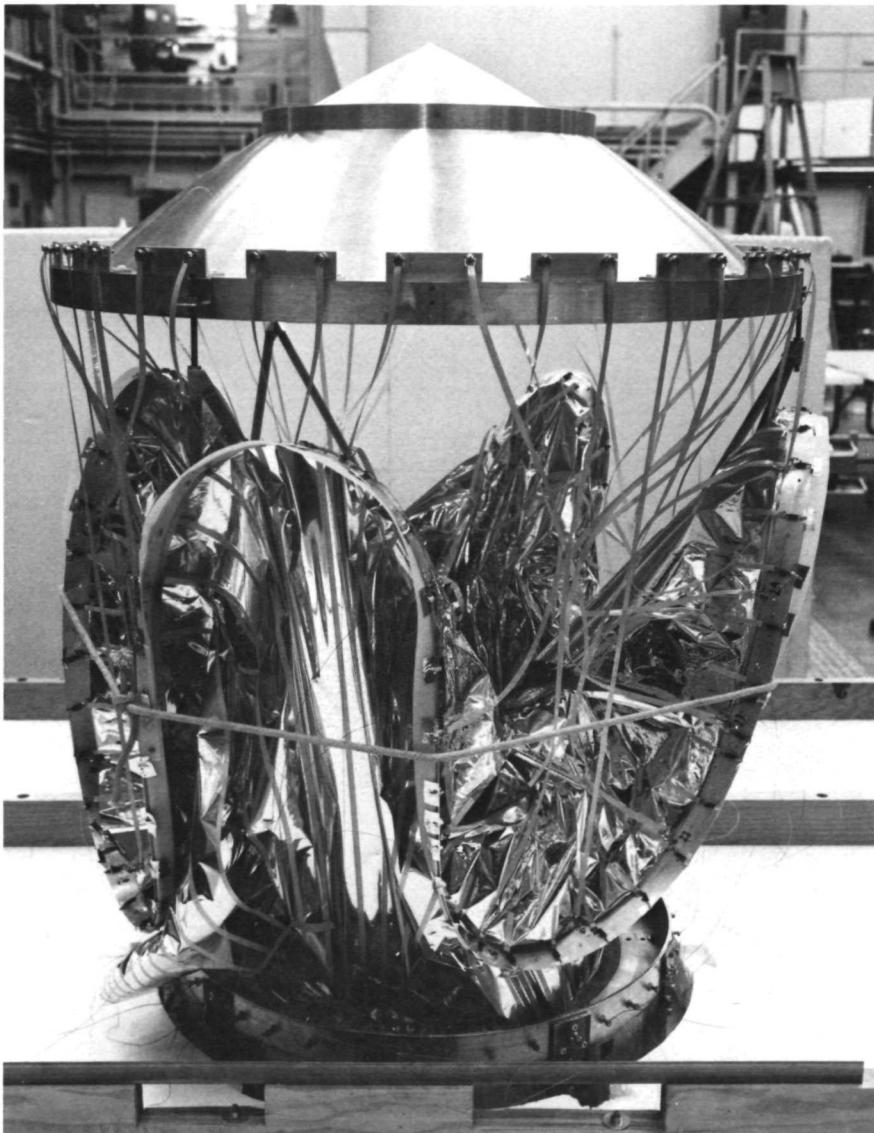


Fig. 10. The 1.83-m (6-ft) diameter furlable conical-Gregorian antenna-spoke-supported ring-membrane design (furled)

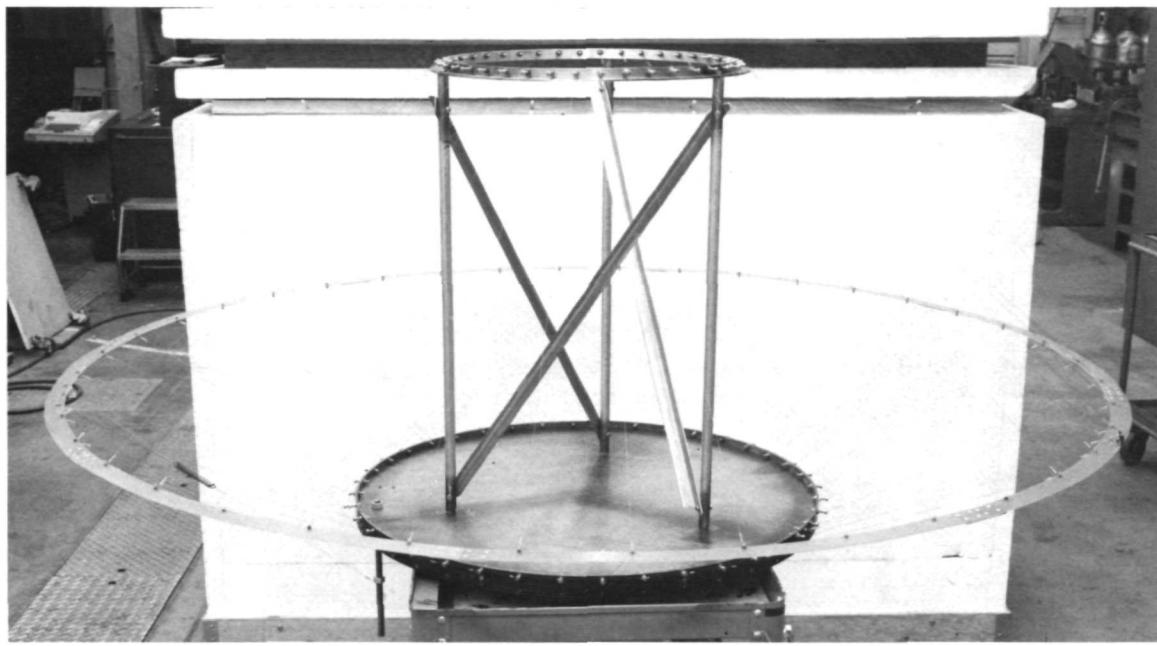


Fig. 11. Spoke-supported ring

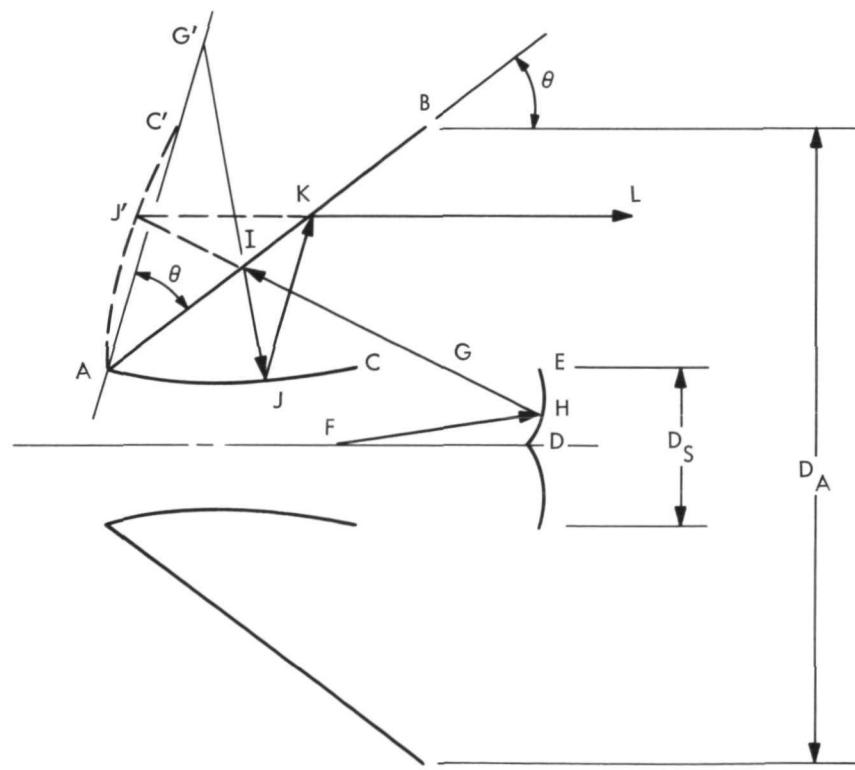


Fig. 12. Quadreflex antenna concept

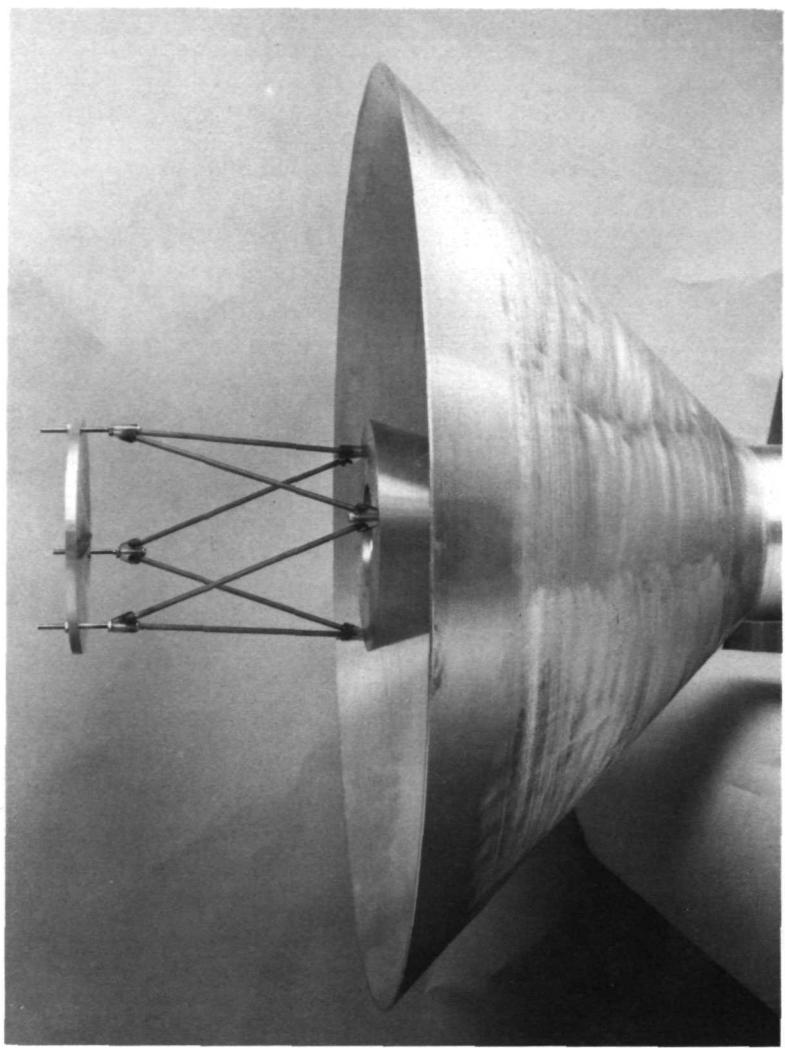


Fig. 13. The 0.762-m (30-in.) diameter rigid Quadreflex antenna

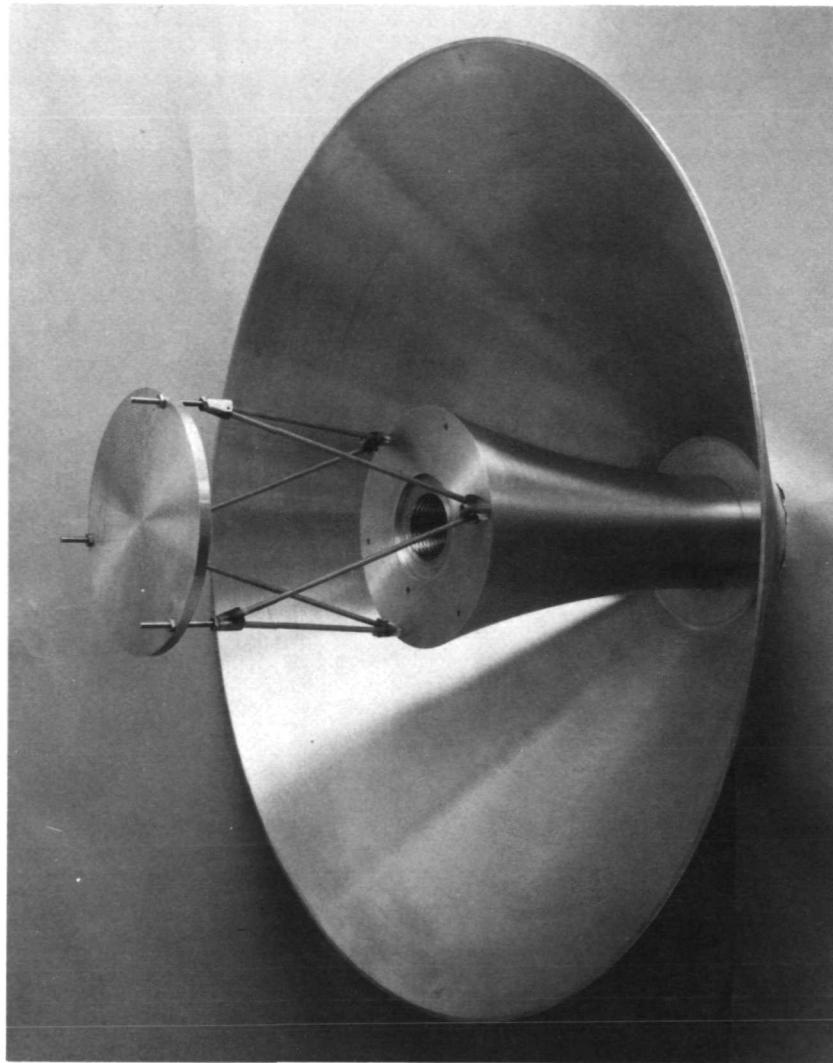


Fig. 14. The 0.762-m (30-in.) diameter rigid Quadreflex antenna

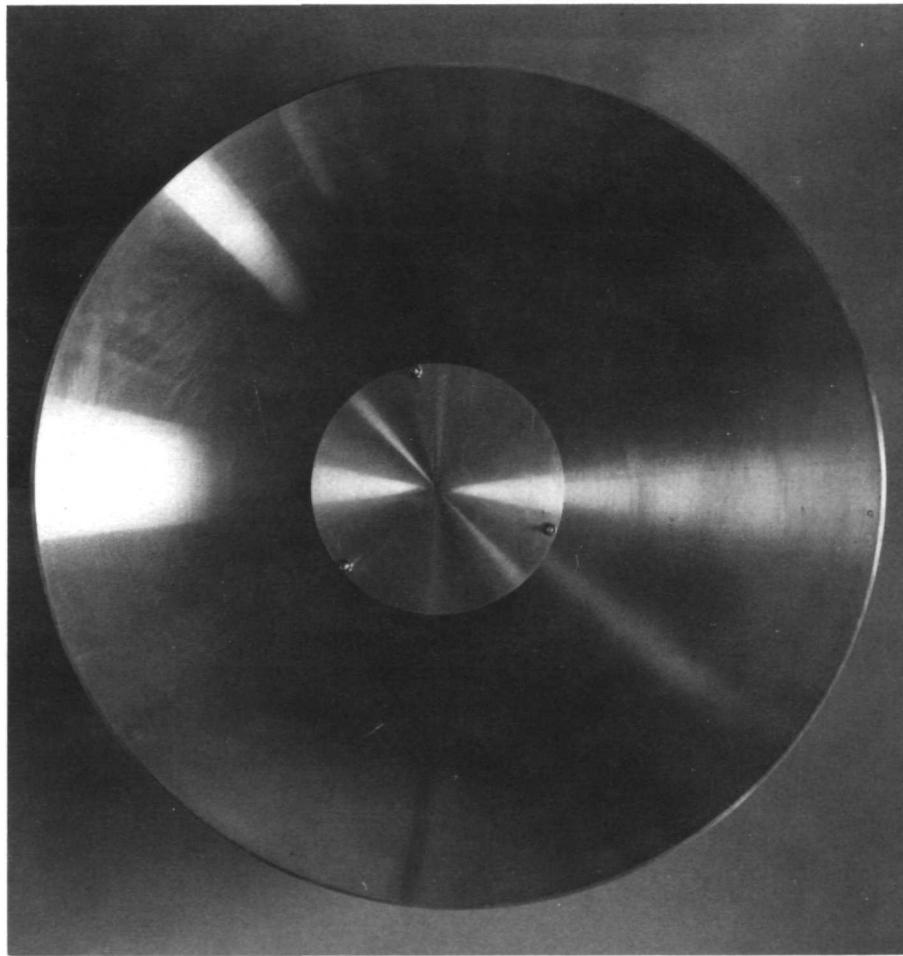


Fig. 15. The 0.762-m (30-in.) diameter rigid Quadreflex antenna

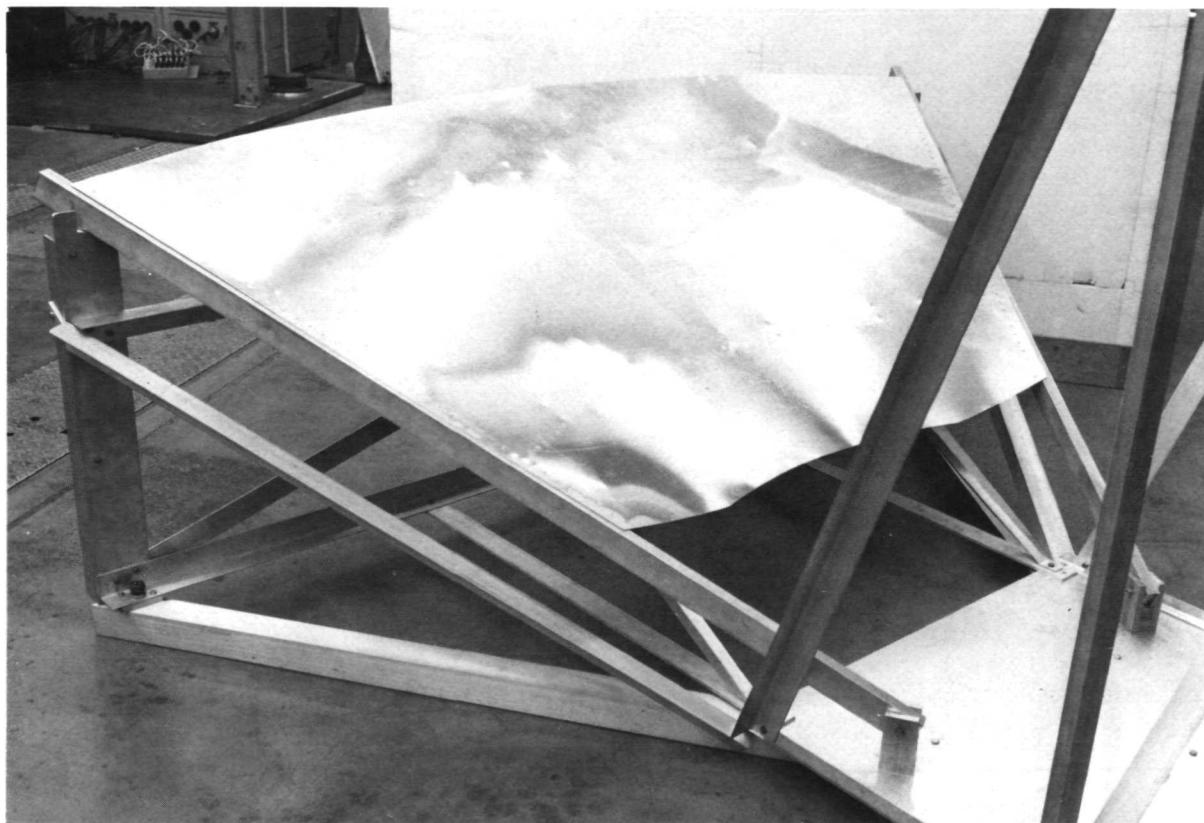


Fig. 16. Test fixture for 60-deg segment of 4.57-m (14-ft) diameter conical-Gregorian main reflector (unfurled)



Fig. 17. Test fixture for 60-deg segment of  
4.57-m (14-ft) diameter conical-  
Gregorian main reflector (furled)

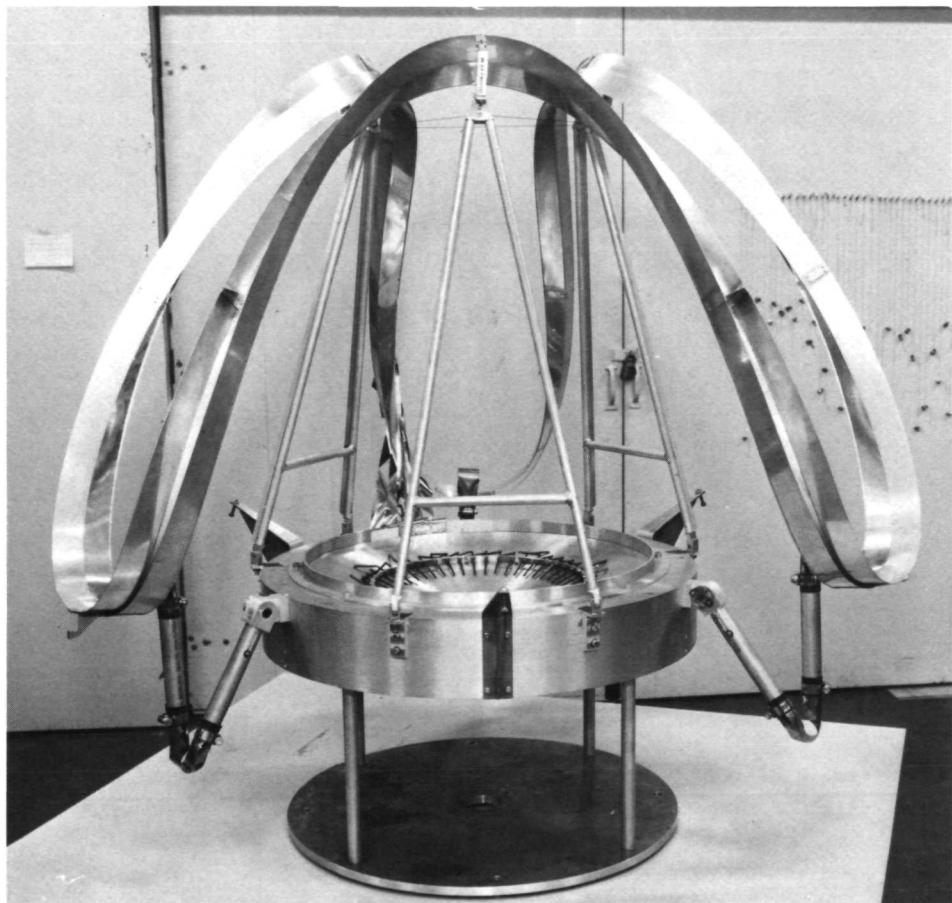


Fig. 18. Rib-supported furlable ring (furled)

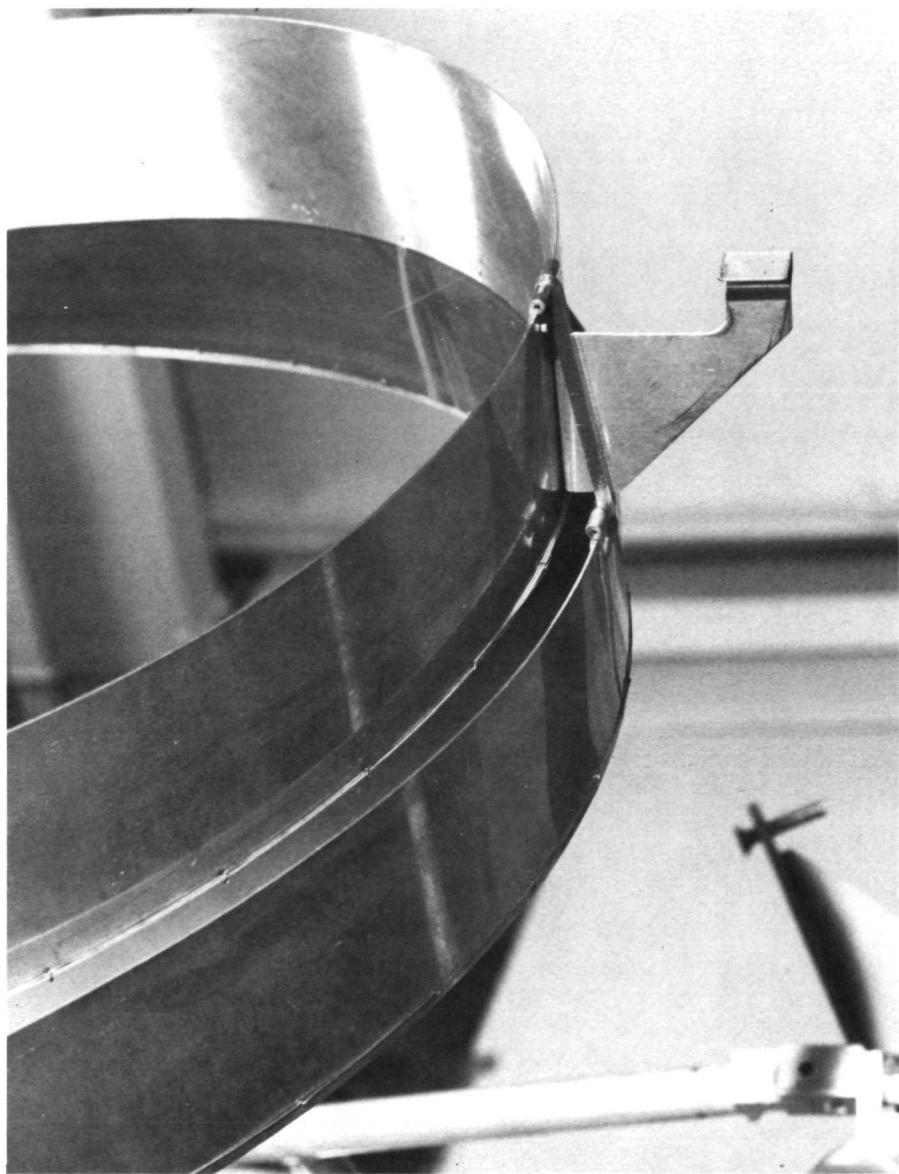


Fig. 19. Furlable rib-supported ring-collapsed configuration

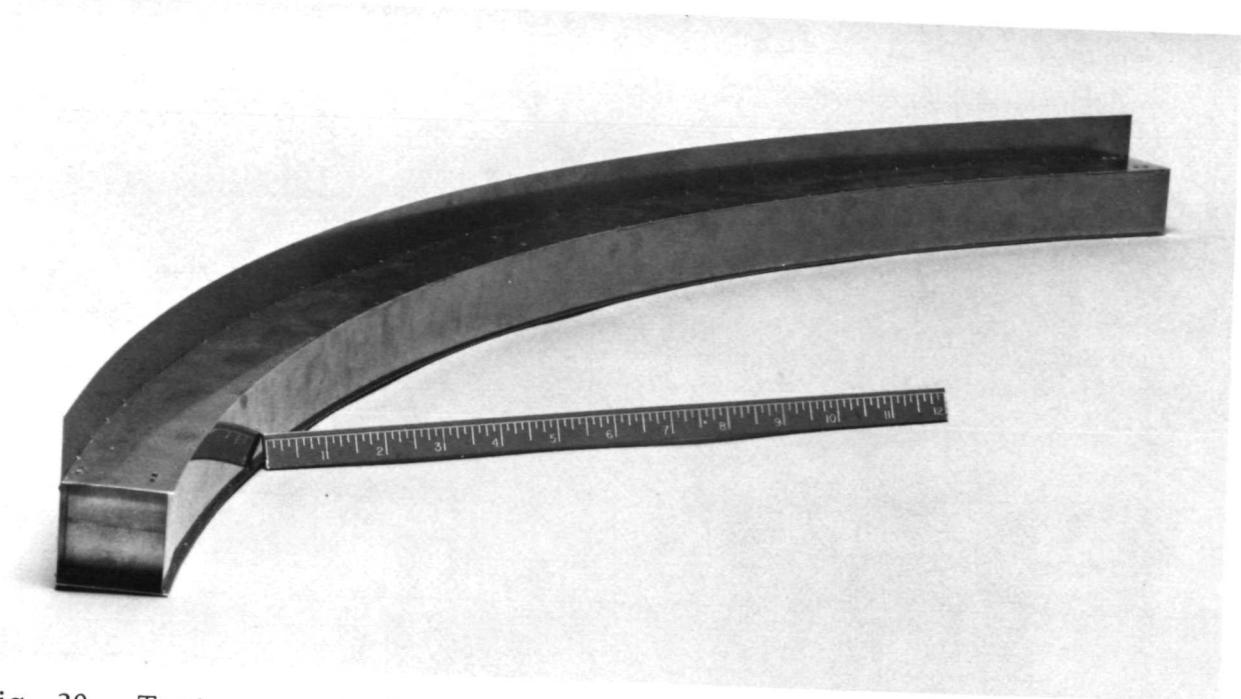


Fig. 20. Test segment of a furlable box section ring (unfurled configuration)

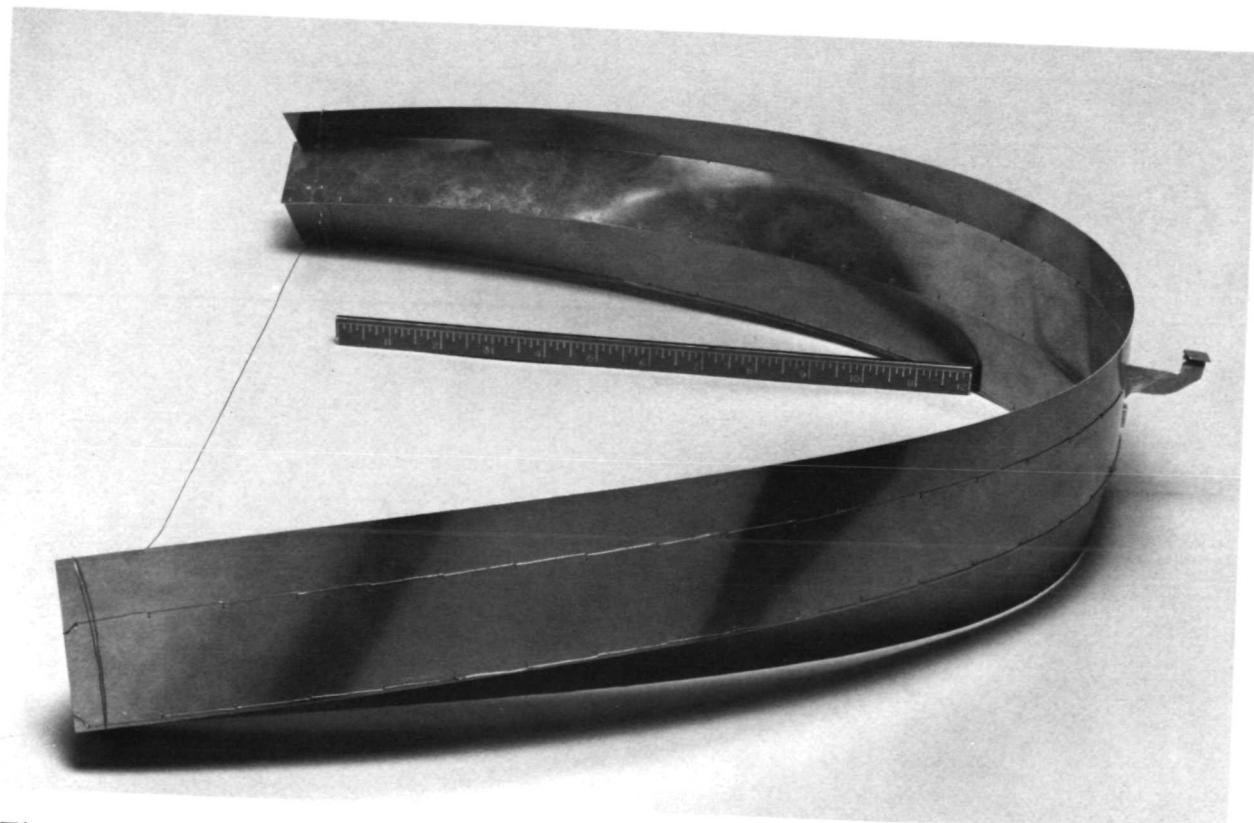


Fig. 21. Test segment of a furlable box section ring (furled configuration)

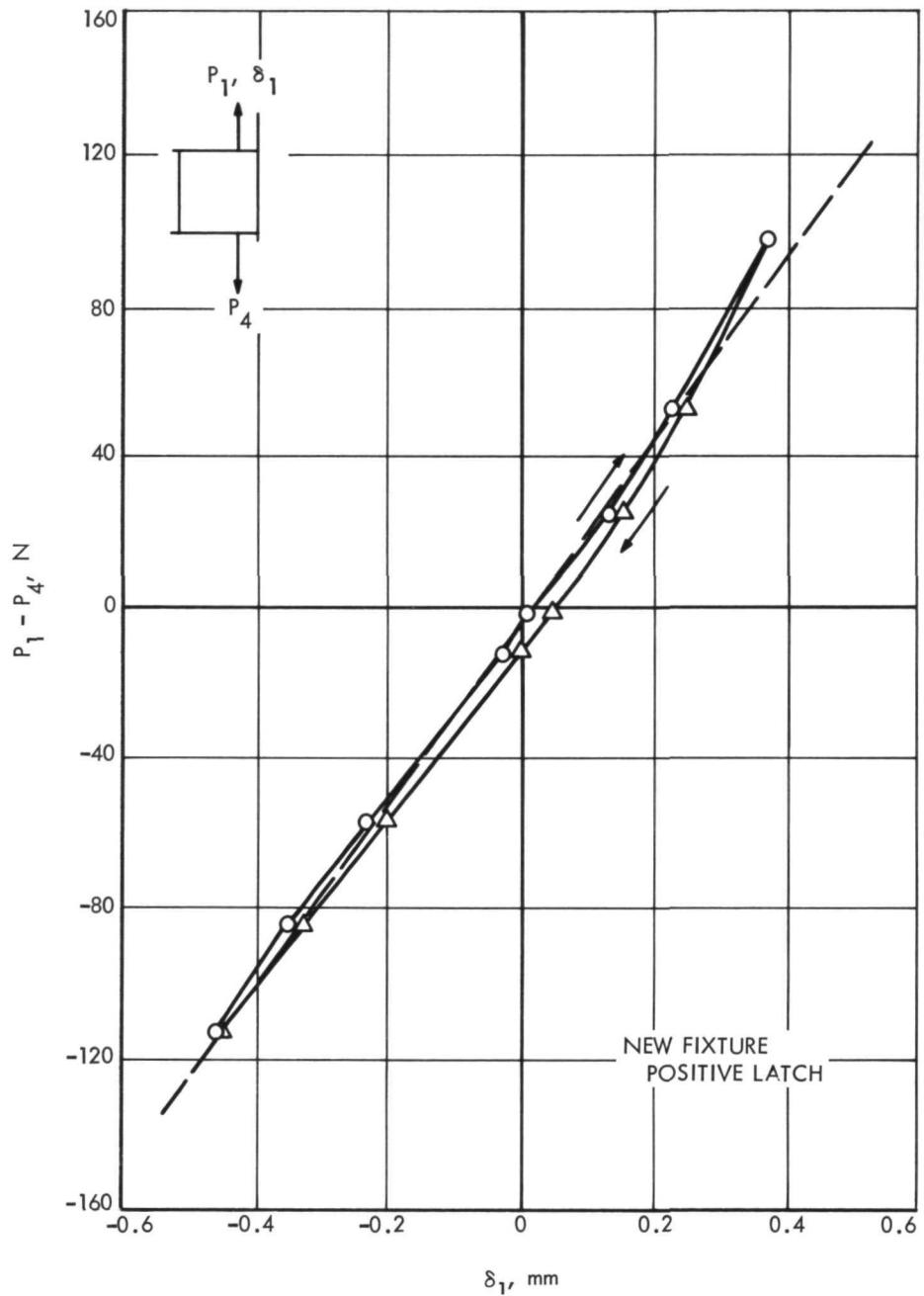


Fig. 22. Load vs deflection for box section ring segment

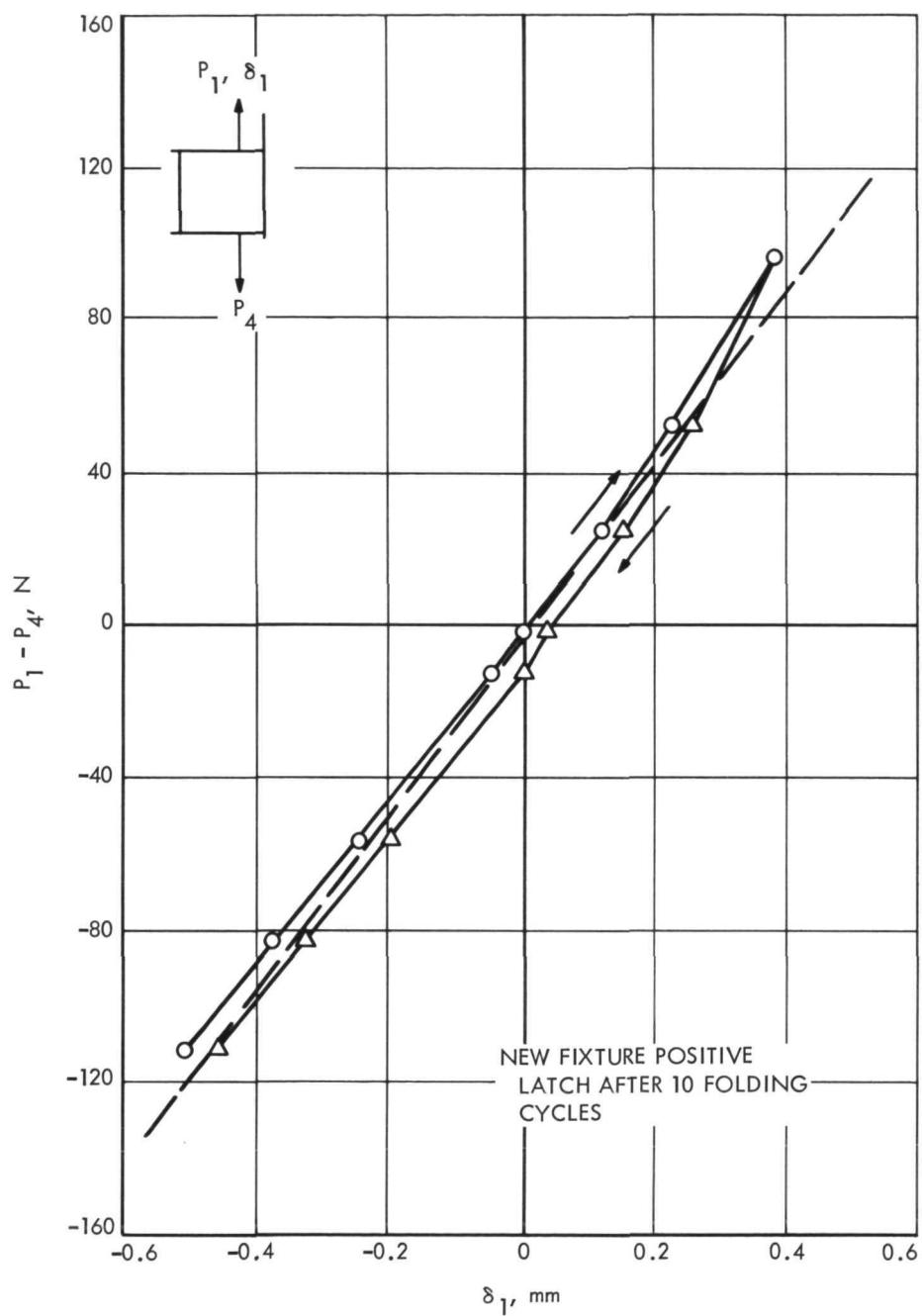


Fig. 23. Load vs deflection for box section ring segment

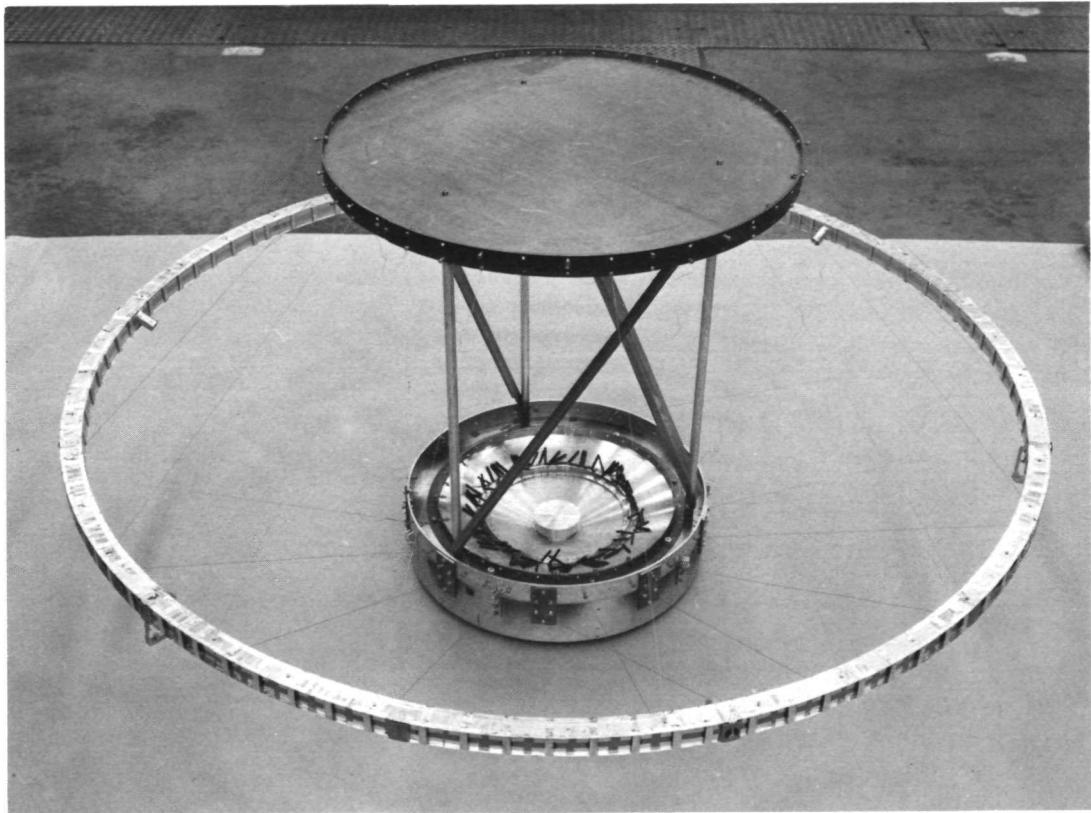


Fig. 24. Spoke-supported box section ring

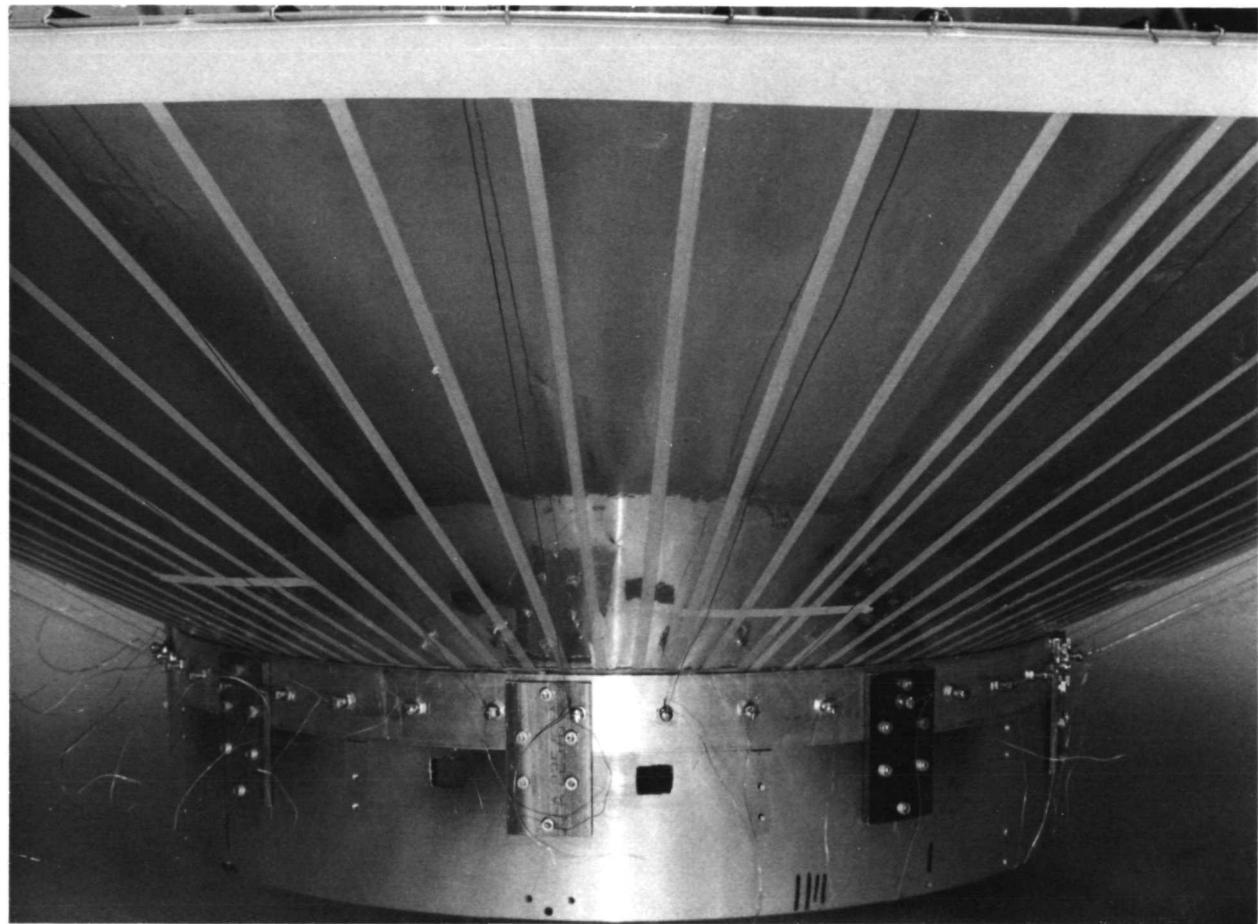


Fig. 25. Spoke-supported ring-membrane reflector, nonilluminated side

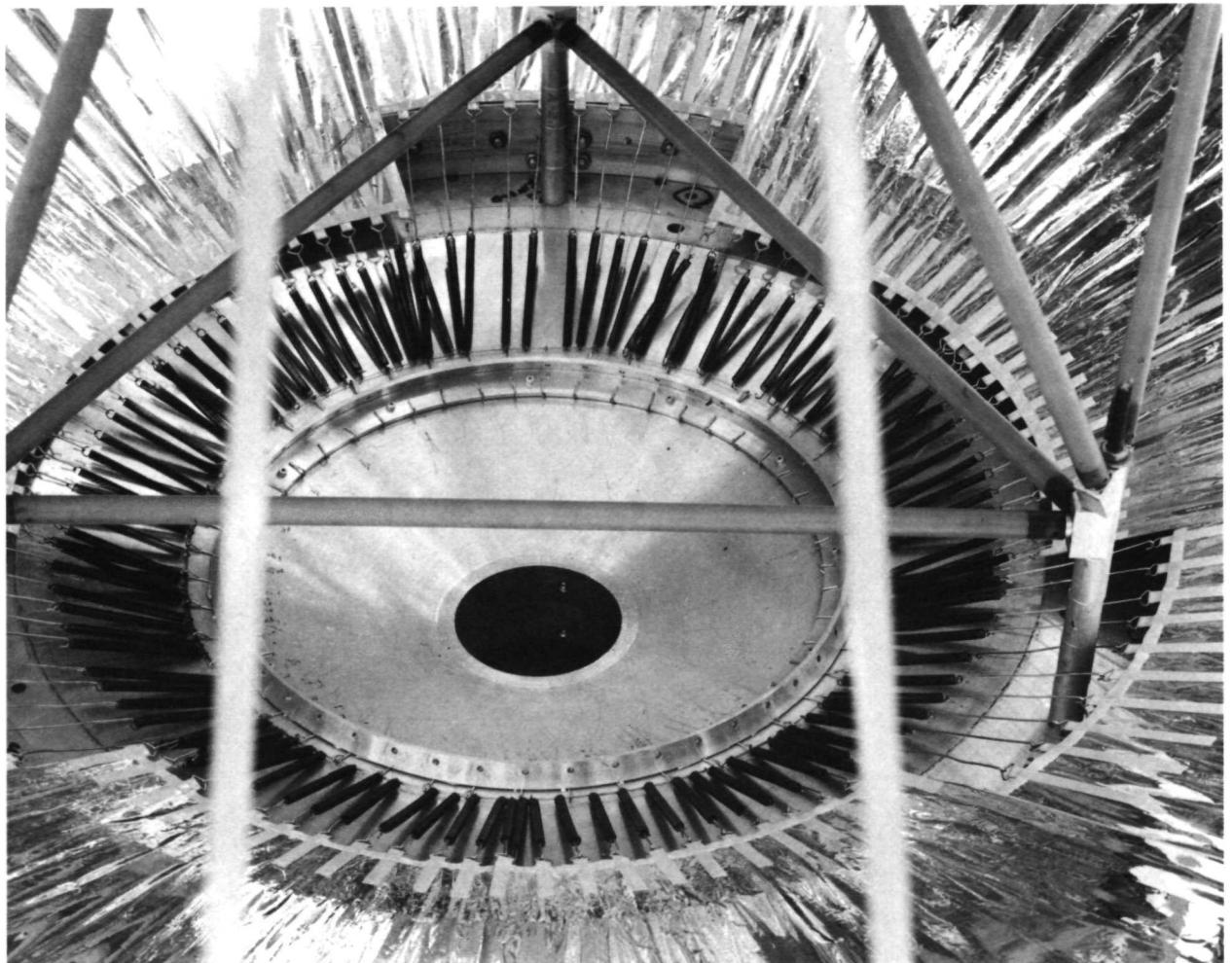


Fig. 26. Spoke-supported ring-membrane antenna, attachment of membrane to hub